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QUARKONIUM PRODUCTION AND DECAY

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ABSTRACT

With new data sets, recently completed analyses and renewed interest, there has been significant progress in addressing existing questions about quarkonia production and decay ... but also new questions and new confrontation with theory. Some highlights include the firm establishment of the η'_c and of the “missing” ψ' decays to 0^-1^- final states, improved information on the nature of the $\psi(3770)$, and the observation of a new, puzzling charmonium-like state at 3872 MeV.

1 Introduction

1.1 Why study Quarkonia?

Quarkonia, bound states of a quark q and its anti-quark \bar{q} , are the QCD equivalents of positronium (bound e^+e^-) in QED. Just as we have learned much about QED from the spectra of positronium, so too we probe the strong force with $q\bar{q}$ bound states. Quarkonia form the simplest, most symmetric strongly interacting system with only two constituents (unlike baryons) and those being identical (unlike mesons with “open” flavor).

The QCD potential is much richer than that of QED. In the simplest formulation, the so-called “Cornell” potential, we have:

$$V(r) = -\frac{4}{3} \cdot \frac{\alpha_s}{r} + k \cdot r \quad (1)$$

The first term mimics the single-photon exchange term in QED and corresponds to one-gluon exchange in QCD, dominating at short distances ($< 0.1\text{fm}$) with large momentum transfers. This is the asymptotically “free” regime which has α_s small, making calculations perturbative (PQCD). The second term, important at larger distance scales ($> 1\text{ fm}$), leads to “confinement” and is in a regime where α_s is large, making calculations non-perturbative.

In this presentation I will discuss only *heavy* quarkonia, $Q\bar{Q}$, with $Q = c$ (charmonium) or b (bottomonium).¹

A big advantage of such $Q\bar{Q}$ systems is that they are not very relativistic: $\beta^2(c\bar{c}) \sim 0.25$ and $\beta^2(b\bar{b}) \sim 0.08$. Therefore non-relativistic QCD (NRQCD) can be used to good approximation, greatly simplifying calculations. Of particular note² is the fact that lattice QCD (LQCD) is making important advances in predictive power for these systems. Further, the physical sizes of $Q\bar{Q}$ states span the range of “free” and “confined”, allowing both aspects of QCD to be studied.

While this presentation concentrates on spectra and decays, one cannot ignore the importance of production in that much is to be learned from the formation of such $Q\bar{Q}$ systems from (virtual) photons and gluons.

The spectra for charmonia and bottomonia are shown in Figure 1, with some typical transitions indicated. Note that the QCD wells for such states are much deeper than the corresponding case for positronium, leading to a much richer spectrum, involving many *hadronic* transitions in addition to those associated with

¹Toponia would be wonderful to study, but the with $m_t > m_W$ the top quark is not sufficiently stable to form hadrons before decaying.

²See the contribution of Matt Wingate to this conference

photon emission. In particular, the $b\bar{b}$ spectrum has three radial excitations below open bottom threshold and enough energy splitting to allow multi-pion or ω emission in transitions among states.

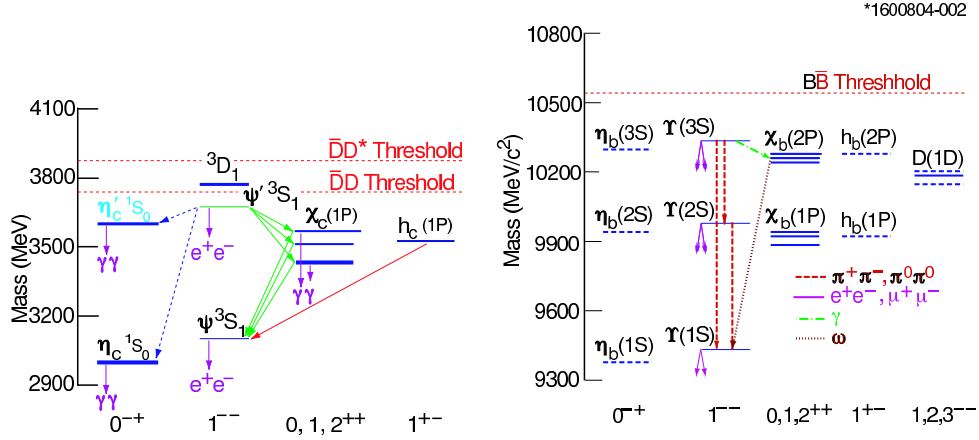


Figure 1: On the left (right) is the charmonium (bottomonium) spectrum below and near open flavor threshold. Shown for $c\bar{c}$ are di-lepton and two-photon decays, which, by t -reversal, are typical production mechanisms. The singlet h_c remains unconfirmed. Shown for $b\bar{b}$ are some of the transitions and decays with $\Upsilon(3S)$ as parent, indicating the diversity of modes and the large amount of available energy release, Q . None of the five singlet η_b or h_b states have yet to be observed.

1.2 Disclaimers and Previous Reviews

This document is a faithful replication of the PIC04 presentation being a non-exhaustive *selection* of topics. Discoveries or updates made after PIC04 will not be included; this is therefore a snapshot of the field on 27 June 2004. One exception is that in the references I give the *current* status of the work.

Of course this review builds on previous efforts, of which two good examples are the PIC03 contribution of Mahlke-Krüger [1] and that from the 2003 Lepton-Photon conference by Skwarnicki[2]. There is also a comprehensive review of quarkonia underway by the Quarkonium Working Group[3]; this CERN Yellow Report is to be completed by September 2004.

2 News on the $Q\bar{Q}$ Spin-Singlets

These states have the spins of Q and \bar{Q} in an anti-symmetric state, so that $S = 0$ and $J = L$. The states with $J^{PC} = 0^{-+}$ (pseudoscalars) are called “ η_Q ” and those with $J^{PC} = 1^{-+}$ are called “ h_Q ”.

For $b\bar{b}$ there is no news on these singlets; the CLEO limits[2] from 2003 have been slightly updated[3] but none of the five have been observed as yet. In the $c\bar{c}$ sector these have been some new measurements of the mass, width and decays of the ground state of charmonium, the η_c , but no startling developments. The lone singlet P state of charmonium, the h_c , remains elusive, with active programs in $p\bar{p}$ production, ψ' decay and $B \rightarrow (c\bar{s})K$ (and maybe others!) all in the hunt.

The biggest news from the spin singlets is the (re)discovery of the η'_c . This had been previously reported by the Crystal Ball experiment [4] in the M1 radiative transition $\psi' \rightarrow \gamma\eta'_c$. But CLEO, with similar sensitivity to the Crystal Ball,³ does not confirm that observation.[2, 5]

But four *new* observations of this radially excited singlet have now been *published*. First, Belle presented a very clean signal (see Fig. 2) in $B \rightarrow \eta'_c K$ decays [6]; they also observed the state in continuum production of double charmonium, $e^+e^- \rightarrow J/\psi \eta'_c$ [7]. This was followed by both CLEO[8] and BaBar[9] publishing their measurements of the η'_c in two-photon fusion.

The four new measurements of the mass of the η'_c are shown in the right portion of Fig. 2, presented[10] as the hyperfine mass splitting between it and the spin-triplet ψ' . The weighted average for this splitting is

$$\Delta'_{hf} = m(\psi') - m(\eta'_c) = (49 \pm 2)\text{MeV} \quad (2)$$

which is roughly *half* the magnitude for this splitting based on the older Crystal Ball measurement of $m(\eta'_c)$, and which is to be compared with $\Delta_{hf} = m(J/\psi) - m(\eta_c) = (117 \pm 2)\text{MeV}$.⁴

The splittings Δ_{hf} and Δ'_{hf} are of some interest because, while the η_c and J/ψ have small radius and are rather deep in the Coulomb-like QCD well, the η'_c and ψ' start to sample the confinement region of the QCD potential. Most theoretical estimates of Δ'_{hf} are higher than the new measurements[10], perhaps because they tend to assume a scalar QCD potential in the confinement region. A recent lattice result[12], which is quenched and thus ignores dynamical light quarks, gives a span of values of $40 < \Delta'_{hf} < 74\text{ MeV}$, depending on input parameters. This situation warrants a new look at models and an unquenched lattice calculation.

³For example, CLEO *does* see the hindered transition to $\gamma\eta_c$ at 8σ significance.

⁴The four results have sufficient spread that using the PDG[11] prescription for scaling uncertainties leads to $49 \pm 4\text{ MeV}$ for this hyperfine splitting.

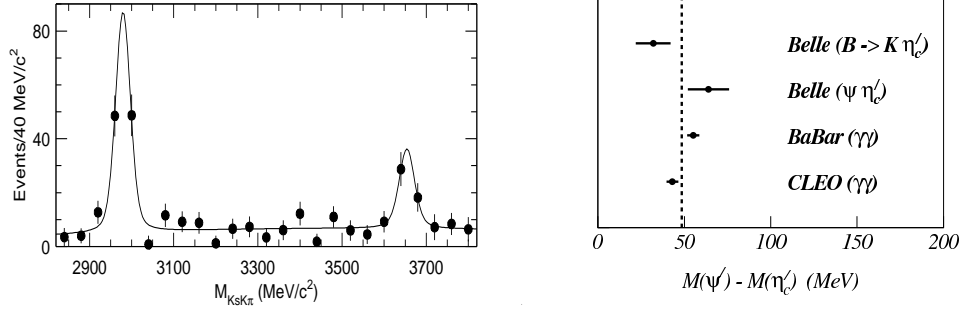


Figure 2: *First observations of the η'_c . On the left is the Belle spectrum in $B \rightarrow K(K_S^0 K \pi)$, showing the well-known η_c , and observation of the η'_c at 3654 MeV. To the right is a summary of the four measurements by Belle, BaBar and CLEO. The weighted average of the hyperfine splitting to the ψ' is 49 ± 2 MeV.*

3 A Sampling of $Q\bar{Q}$ Vector Results

The vector ψ and Υ resonances are directly produced by e^+e^- colliders via annihilation to a virtual photon. With large data sets recently obtained by CLEO at CESR and BES at BEPC, it is not surprising that these two experiments dominate this portion of the onia news.

3.1 $\mathcal{B}_{\mu\mu}$ for the Υ States

Good measurements of $\mathcal{B}(\Upsilon(nS) \rightarrow \mu^+\mu^-) \equiv \mathcal{B}_{\mu\mu}(nS)$ are particularly important. They play a crucial role in determining the resonance widths, in that these states are significantly more narrow than the collider beam energy spread. CLEO plans to measure Γ_{ee} to within a few percent from its careful scans of the resonant line shapes. Learning Γ_{tot} to $\sim 5\%$ thus means measuring $\mathcal{B}_{\mu\mu}$ to similar precision. Also, $\mathcal{B}_{\mu\mu}$ is needed to evaluate many other important branching fractions, in that often what is really measured is the product $\mathcal{B}(X \rightarrow Y\Upsilon(nS)) \cdot \mathcal{B}(\Upsilon(nS) \rightarrow \mu^+\mu^-)$.

CLEO has both the statistical power (over 5 million of each of the three bound-state Υ resonances) and the control of systematics to make such precise measurements of $\mathcal{B}_{\mu\mu}$. Their preliminary results[13] are $\mathcal{B}_{\mu\mu}(nS) = (2.53 \pm 0.02 \pm 0.05)\%$, $(2.11 \pm 0.03 \pm 0.05)\%$, and $(2.44 \pm 0.07 \pm 0.05)\%$ for $n = 1, 2, 3$, respectively. For the $\Upsilon(1S)$ this agrees with the current PDG average[11], but the results for the two radial excitations are significantly higher than in the PDG. These results are shown graphically in Fig. 3.

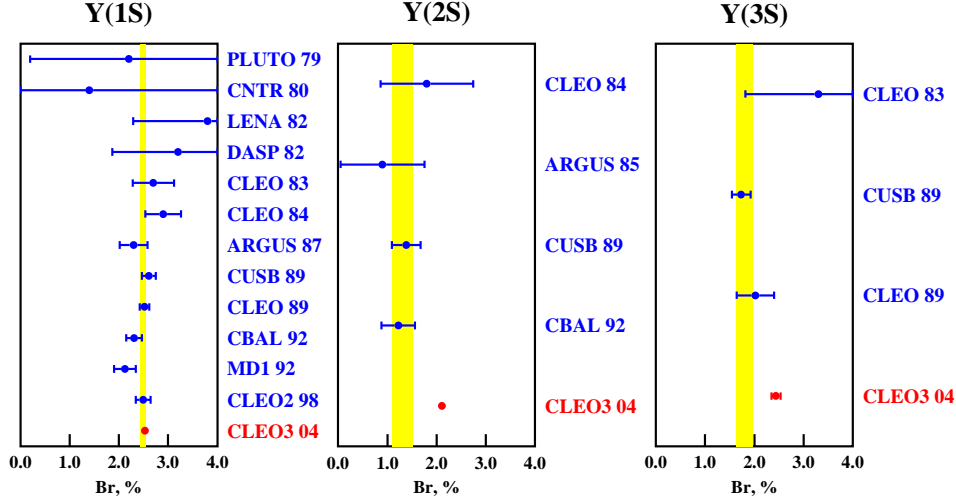


Figure 3: Comparison of the new CLEO results for $B_{\mu\mu}$ to prior measurements and, in the vertical stripe, the current PDG world average.

3.2 From $Q\bar{Q}$ to $Q'\bar{Q}'$

The *color octet* model was developed to help explain large charmonium production rates at hadron colliders by having $c\bar{c}$ produced from a single gluon (hence, as a color *octet* state) and then perturbatively shedding a soft gluon before emerging from the interaction. Models having two gluons form the $c\bar{c}$ meson as a final state particle are called *color singlet* models. A good place to test such octet[14] and singlet[15] models is the glue-rich environment of Υ decay. While both predict roughly equal rates for $\Upsilon \rightarrow J/\psi X$, the singlet momentum spectrum is much softer in that a second c and \bar{c} must hadronize as charmed mesons.

CLEO[16] has measured $\mathcal{B}(\Upsilon \rightarrow J/\psi X) = (6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$ which includes feed-down from other charmonia (ψ' , ...); this is consistent with the predictions of the models. However the measured J/ψ momentum spectrum is much too soft to support the color octet model. Further the observation of $\Upsilon \rightarrow \psi' X$, with $\mathcal{B}(\Upsilon \rightarrow \psi' X) = (0.41 \pm 0.11 \pm 0.08) \times \mathcal{B}(\Upsilon \rightarrow J/\psi X)$, and the decay rates of Υ to χ_{c1} and χ_{c2} are above the octet model predictions.

3.3 ψ' v. J/ψ : The “12%” Puzzle

Major progress has been made on a long standing puzzle in vector charmonium. Because three-gluon decay to hadrons of $c\bar{c}$ and electro-magnetic production/decay of such states via a virtual photon both depend on the wave-function overlap ($|\Psi(0)|^2$) one naively expects:

$$\frac{\mathcal{B}(\psi' \rightarrow h)}{\mathcal{B}(J/\psi \rightarrow h)} \equiv Q_h = Q_{ee} \equiv \frac{\mathcal{B}(\psi' \rightarrow e^+e^-)}{\mathcal{B}(J/\psi \rightarrow e^+e^-)} \sim 12\% . \quad (3)$$

There are many complications, caveats and considerations⁵ to this “equality”, so one should not be too surprised at small deviations. However, two particular hadronic modes, $\rho\pi$ and $K^*\bar{K}$, both vector-pseudoscalar (V-P), are blatant violators of Eqn. 3, with limits[11] of $Q_h/Q_{ee} < 0.1$.

Big new data sets at BES/BEPC (14 million ψ' decays and 6.4 pb^{-1} of continuum) and CLEO-c/CESR-c (~ 3 million ψ' decays from 5.5 pb^{-1} of luminosity and $\sim 20 \text{ pb}^{-1}$ of continuum) have come to rescue. BES has presented evidence[17] for the modes $K^{*0}\bar{K}^0$ and $K^{*+}K^-$ in the final state $K_S^0 K^\pm \pi^\mp$, as depicted in their Dalitz plot in Fig. 4. There is a large signal in the neutral mode, giving $\mathcal{B}(\psi' \rightarrow K^{*0}\bar{K}^0) = (15.0 \pm 2.1 \pm 1.7) \times 10^{-5}$ and $Q_h = (3.6 \pm 0.7)\%$ (slight suppression relative to J/ψ). The charged mode has a significant signal as well (3.5σ) and gives $\mathcal{B}(\psi' \rightarrow K^{*+}K^-) = (2.9 \pm 1.3 \pm 0.4) \times 10^{-5}$ and $Q_h = (0.6 \pm 0.3)\%$ (heavily suppressed relative to J/ψ). Thus, there is a large difference in these isospin-related final states. The small continuum sample of BES does not allow for a subtraction of this possible background source.

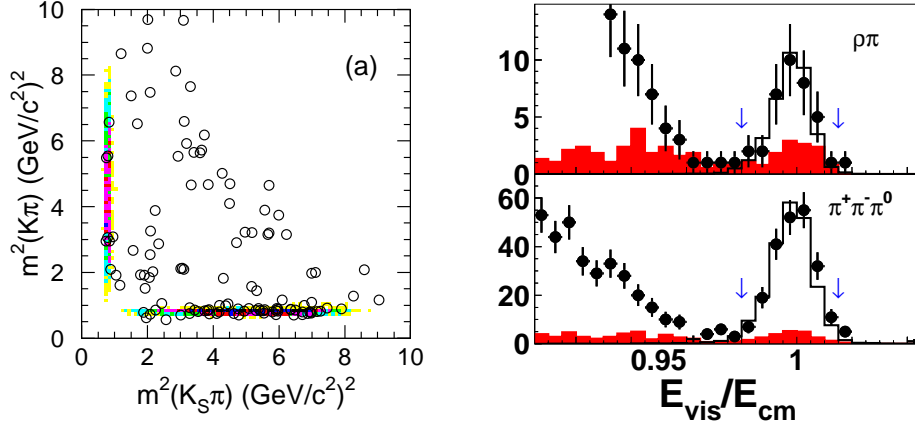


Figure 4: On the left is the BES Dalitz plot from their analysis of $\psi' \rightarrow K_S^0 K^\pm \pi^\mp$; there is a clear horizontal (vertical) enhancement corresponding to $K^{*0} K_S^0$ ($K^{*\mp} K^\pm$) decays. On the right is the CLEO distribution of fractional visible energy in $\psi' \rightarrow \pi^+ \pi^- \pi^0$; the upper of the two spectra has had a ρ meson selected from the associated Dalitz plot projections.

⁵For example, the running of α_s , form factor dependences on S , helicity conservation issues, non-relativistic effects, interference with continuum, ...

CLEO has presented[18] results for Q_h/Q_{ee} for a large number of modes, including, for the first time, $\rho\pi$ in the $\pi^+\pi^-\pi^0$ final state. They have made a continuum *subtraction*, but assume no interference contribution. After projecting the Dalitz plot to obtain samples of ρ^0 and ρ^\pm , they extract the yield by demanding no missing energy, as shown to the right of Fig. 4. Their results in the $\pi^+\pi^-\pi^0$ final state are $Q_{\rho\pi}/Q_{ee} = 0.016 \pm 0.006$ and $Q_{\pi^+\pi^-\pi^0}/Q_{ee} = 0.053 \pm 0.011$.

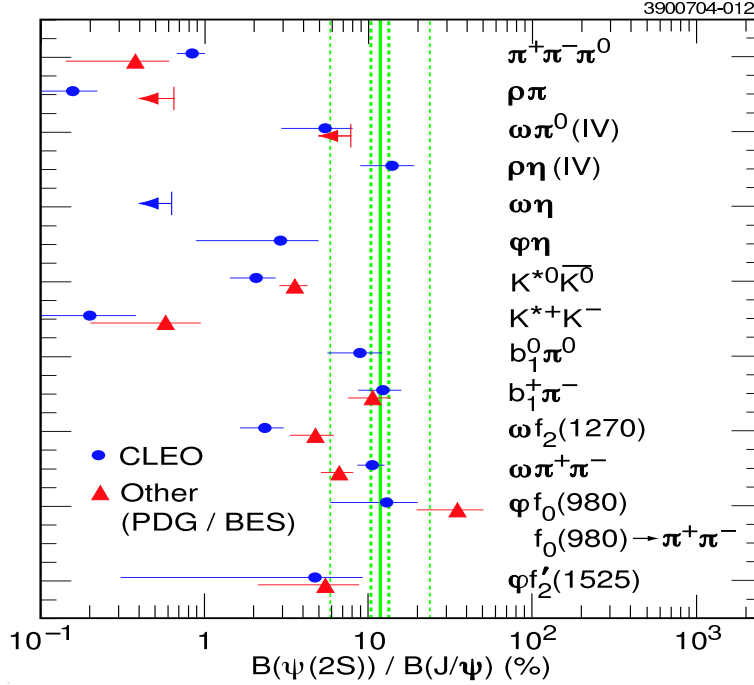


Figure 5: Q_h , the ratio of branching fractions to specific hadronic states for the $\psi' = \psi(2S)$ and J/ψ . The solid vertical line is the naive expectation for this ratio: $Q_h = Q_{ee} = 12\%$. The inner dotted lines show the present uncertainties in Q_{ee} ; the outer dotted lines are at $Q_{ee}/2$ and $2Q_{ee}$.

The status of this “puzzle” is represented pictorially in Fig. 5. Some of the important features: (i) the $\rho\pi$ and K^*K modes have now been *measured*; (ii) the isospin violating (and hence, electro-magnetic) modes seem to support the “12% rule”; (iii) the isospin-related modes $K^{*0}\bar{K}^0$ and $K^{*+}K^-$ seem quite different in their behavior; (iv) the A-P states do not seem suppressed, while V-T states are suppressed by about a factor of ~ 5 ... not nearly as much as the V-P states $\rho\pi$ and $K^{*+}K^-$.

An open question is whether the suppression is due to S - D mixing, meaning a possible enhancement in V-P decays of the $\psi(3770)$, by virtue of common virtual $D\bar{D}$ loops.

3.4 ψ' v. J/ψ : Relative Phases

Another interesting comparison of the J/ψ and ψ' wave-functions is the relative phase for each of these to decay strongly via $c\bar{c}$ annihilation to three gluons (“S”) as opposed to electro-magnetically via a single virtual photon (“EM”). The decay $(c\bar{c}) \rightarrow K^+K^-$ can proceed by either of these two routes, but $(c\bar{c}) \rightarrow K^0\bar{K}^0$ is purely a strong decay (SU(3) symmetry) and $(c\bar{c}) \rightarrow \pi^+\pi^-$ is purely electro-magnetic (G-parity). Hence

$$|\mathcal{A}(K^+K^-)|^2 = |\mathcal{A}(\pi^+\pi^-)|^2 + |\mathcal{A}(K^0\bar{K}^0)|^2 + 2 \cdot |\mathcal{A}(\pi^+\pi^-)| \cdot |\mathcal{A}(K^0\bar{K}^0)| \cdot \cos\phi_{S,EM}. \quad (4)$$

Previously BES[19] has measured $\cos\phi_{S,EM}(J/\psi) = (90 \pm 10)^\circ$. With 14×10^6 ψ' events they have observed a large sample of mono-chromatic K_S^0 candidates from which they obtain[20] $\mathcal{B}(\psi' \rightarrow K_S^0 K_L^0) = (5.24 \pm 0.47 \pm 0.48) \times 10^{-5}$. Combining this with various prior results on the $\pi^+\pi^-$ and K^+K^- channels gives $\cos\phi_{S,EM}(\psi') = (-89 \pm 29)^\circ$ or $(121 \pm 27)^\circ$. Thus, $\cos\phi_{S,EM}(\psi')$ and $\cos\phi_{S,EM}(J/\psi)$ are consistent.

BES also re-measured[21] $\mathcal{B}(J/\psi \rightarrow K_S^0 K_L^0)$ from their 55 million J/ψ sample as $(1.82 \pm 0.04 \pm 0.13) \times 10^{-4}$, meaning $\mathcal{B}(\psi' \rightarrow K_S^0 K_L^0) / \mathcal{B}(J/\psi \rightarrow K_S^0 K_L^0) = (29 \pm 4)\%$, somewhat large for the “12% rule” represented by Eqn. 3.

4 $Q\bar{Q}$ States with $L = 2$ (“D”)

Bottomonium (see Fig. 1) is the only QCD system with a stable member that has two units of orbital angular momentum. This makes these “D” states important to test spin-orbit and high-L effects in both models and LQCD. The CLEO analysis of the four photon cascade $\Upsilon(3S) \rightarrow \gamma_1 \gamma_2$ “D” $\rightarrow \gamma_1 \gamma_2 \gamma_3 \gamma_4 \ell^+ \ell^-$ is now final[22]. A single state is observed at $M_D = (10161 \pm 0.6 \pm 1.6)$ MeV at $> 10\sigma$ significance. The decay rate and intermediate χ'_b and χ_b assignments are consistent with this being the 1^3D_2 state.

The impact of this result on LQCD[23] is shown in the left portion of Fig. 6. Plotted first results for nine “golden” quantities from analyses that were “quenched”, thus not incorporating the effects of dynamical light quarks. Next to this are recent *unquenched* results with uds quarks included. None of the nine quantities are used as “input”. These show LQCD being able to attain better than 5% accuracy in these quantities, one of which is the D-S splitting in bottomonium.

Turning to charmonium, there is the continuing puzzle of the nature of the $\psi(3770)$, which one can characterize as being $\alpha \cdot n^3S_1 + \beta \cdot 1^3D_1 + \gamma \cdot D\bar{D}$. Clearly $\alpha \neq 0$ in that the $\psi(3770)$ is directly produced in e^+e^- annihilation. Belle[24] has

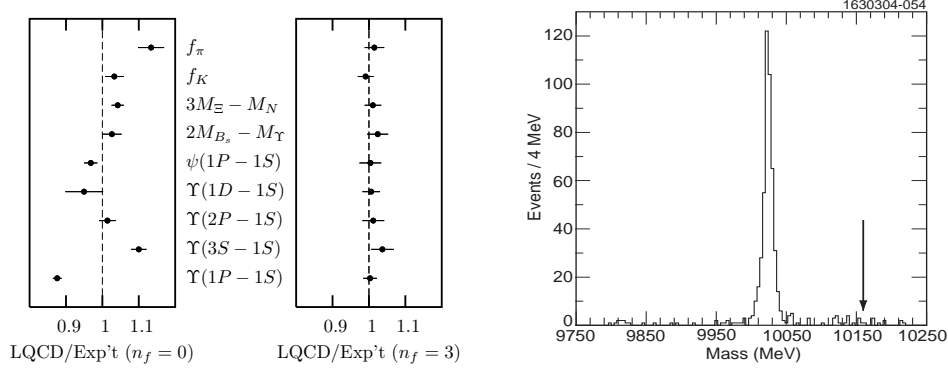


Figure 6: On the left is the current status of nine “golden” quantities by which to compare lattice QCD calculations and experiment, with the most recent entry being the “D-S” mass splitting in $b\bar{b}$. To the right is recoil mass against the two photons in $\Upsilon(3S) \rightarrow \gamma\gamma[\pi^+\pi^-\Upsilon(1S)]$. The observed peak is due to E1 cascade to the $\Upsilon(2S)$; no rate is observed for decay from the new $\Upsilon(1^3D_2)$ state.

recently observed a solid $\psi(3770)$ signal in $B^+ \rightarrow K^+ D^0 \bar{D}^0$, from which they extract $\mathcal{B}(B \rightarrow K\psi(3770)) = (4.8 \pm 1.1 \pm 0.7) \times 10^{-4} \sim 2/3 \mathcal{B}(B \rightarrow K\psi')$. This comparison would imply that there is large S-D mixing, although color-octet models might be able to accommodate this rate for a pure “D” state ($\beta \sim 1$).

An important mode to investigate would seem to be $\psi(3770) \rightarrow \pi^+\pi^- J/\psi$. A compilation of MarkII and BES results[25] gives $\Gamma(\pi^+\pi^- J/\psi) = (43 \pm 14)$ keV, which is near the *upper bound* for this rate as analyzed by CLEO[2]. The Kuang-Yan prediction[26] for this rate is 20-107 keV, depending on the level of S-D mixing; however, the CLEO limit[22], depicted in Fig. 6, for $\Upsilon(1D) \rightarrow \pi^+\pi^- J/\psi$, is some seven times below[27] that predicted for a such a D state in the Kuang-Yan model, casting doubt on whether the $\Gamma(\pi^+\pi^- J/\psi)$ measured for the $\psi(3770)$ is *really* consistent with theoretical expectations. Once the decay to $\pi^+\pi^- J/\psi$ is solidly observed, the angular distributions of the decay products should help sort out[28] α, β, γ .

5 $Q\bar{Q}$ States with $L = 1$ (“ χ ”)

Although copiously produced in E1 transitions from the vector mesons directly obtained in e^+e^- annihilation, rather little is known about these χ_c and χ_b states.

CLEO has finalized[29] its analysis of $\chi'_{bJ} \rightarrow \omega\Upsilon(1S)$ for $J = 1, 2$. There is so little Q value for this decay that the process is kinematically forbidden for $J=0$! Nonetheless, the quoted branching fractions are large: $\mathcal{B}(\chi'_{b1} \rightarrow \omega\Upsilon(1S)) = (1.6 \pm 0.3 \pm 0.2)\%$ and $\mathcal{B}(\chi'_{b2} \rightarrow \omega\Upsilon(1S)) = (1.1 \pm 0.3 \pm 0.1)\%$, to be compared to the $\sim 7\%$ branching fraction for the E1 photon transitions $\chi'_{bJ} \rightarrow \gamma\Upsilon(1S)$. The rates for

this ω transition are therefore roughly equal for $J = 1$ and $J = 2$, as predicted[28].

The BES collaboration has used its χ_c sample to test the color-octet model in baryonic decays. The color singlet model is unable to generate the observed rates for, *e.g.*, $\chi_{cJ} \rightarrow p\bar{p}$. Adding in color octet contributions[30] predicts that the ratio $\mathcal{R}_B = \Gamma(\Lambda\bar{\Lambda})/\Gamma(p\bar{p})$ is ~ 0.60 and ~ 0.45 for χ_{c1} and χ_{c2} decays, respectively. The BES collaboration [31] last year reported on the $\Lambda\bar{\Lambda}$ channel; now they have very clean signals for all three J states decaying into $p\bar{p}$. These lead to experimental values of $\mathcal{R}_B = 4.6 \pm 2.3$ and 5.1 ± 3.1 for $J = 1$ and $J = 2$. While the uncertainties are large, they nonetheless tend to show the $\Lambda\bar{\Lambda}$ channel enhanced, not suppressed, with respect to $p\bar{p}$.

6 The $X(3872)$ - New Quarkonium-like State !!

The hottest onia news at last year's Lepton-Photon meeting[2] was the observation ($> 10\sigma$) by Belle[32] of a new "charmonium-like" state at 3872 MeV produced in $B^+ \rightarrow K^+ X$ and decaying to $J/\psi \pi^+ \pi^-$. Since then, it has been seen clearly by CDF[33] in hadro-production (as reported at QWGII[3] and shown in Fig. 7) as well as by D0[34] and BaBar[35].

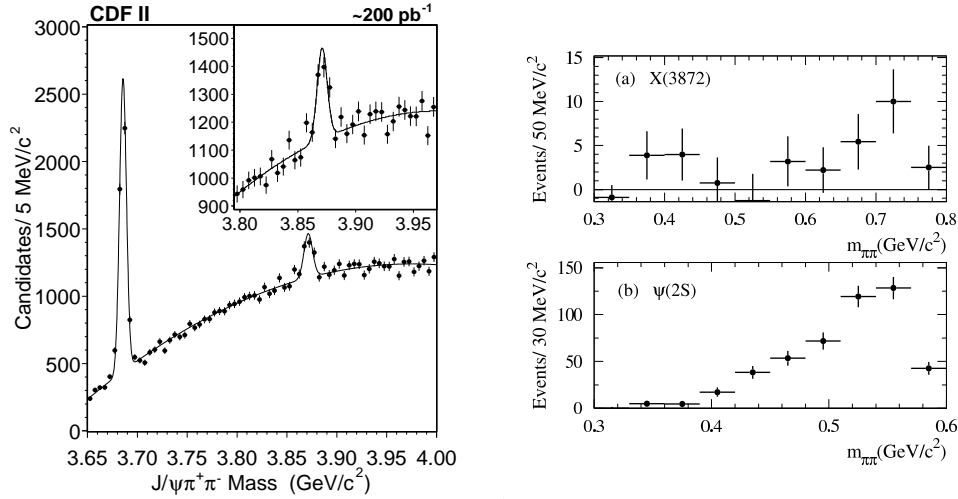


Figure 7: At QWGII, CDF confirmed the Belle observation of the $X(3872)$, showing the left plot, with clear evidence of the ψ' and the X ($> 11\sigma$ significance); the events were required to have a di-pion invariant mass in excess of 500 MeV. To the right are the BaBar spectra of this di-pion mass for both the X and ψ' regions.

Of particular note is the nature of the $\pi\pi$ system in the X decay. Belle[32] reported a dipion mass ($m_{\pi\pi}$) consistent with the decay $X \rightarrow \rho J/\psi$, which would

imply that $C_X = +1$. This tendency toward large $m_{\pi\pi}$ was actually *used* by CDF and D0 to enhance their signals. Fig. 7 also shows the $m_{\pi\pi}$ spectrum as reported by BaBar[35] for the X and for their large $\psi'(3686)$ sample. Is the high-mass region *really* a ρ or is it just a mimic of the similar shape in ψ' decay? Is there a second, low-mass peak in the $m_{\pi\pi}$ spectrum, similar to what has been observed[36] in $\Upsilon(3S) \rightarrow \pi\pi\Upsilon(1S)$? Do experiments see the more difficult channel $X \rightarrow \pi^0\pi^0$, which would imply $C_X = -1$? One should keep watching this di-pion system as the sample sizes increase with more data at the Tevatron and the B -factories.

D0[34] has looked at six aspects of the production and decay of the $X(3872)$ as compared to the $\psi'(3686)$: p_T to the jet, range of rapidity, isolation, decay length distribution, helicity angles of the muons and of the pions. In all cases the X looks like the well-established $c\bar{c}$ state.

The four-experiment average has $M_X = 3872.2 \pm 0.5$ MeV, tantalizingly close to the mass of a $D^0 D^{0*}$ pair at[11] 3871.2 ± 0.9 MeV but significantly below the corresponding charged system, with a mass of a $D^+ D^{*-}$ pair being 3879.3 ± 1.0 MeV. This “coincidence”, coupled with the fact[32, 35] that

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ X(3872)) \cdot \mathcal{B}(X \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(B^+ \rightarrow K^+ \psi'(3686)) \cdot \mathcal{B}(\psi' \rightarrow J/\psi \pi^+ \pi^-)} = 0.062 \pm 0.011, \quad (5)$$

leads to the conjecture that the $X(3872)$ has a $c\bar{c}$ “core” and a large $D^0 D^{0*}$ “molecular” component.

There has been a lot of activity (with a lot more ongoing!) to determine the quantum numbers of this new state. Searches by Belle[32] for the decays $\gamma\chi_{c1}$, $\gamma\chi_{c2}$, and $\gamma J/\psi$ have shown it unlikely that $X(3872)$ is 1^3D_2 , 1^3D_3 , or $\chi'_c(2^3P_J)$, respectively. Other studies of BES and CLEO data[37] in radiative return and two-photon fusion production tend to disfavor vector states ($J^{PC} = 1^{--}$) and those with even J and positive C -parity.

This is certainly a most curious state and hopefully much more will be known about it by PIC2005!

7 Summary and Acknowledgments

As is evident, heavy quarkonia continue to be a source of great energy and excitement, with many recent advances and many open questions: a stable “D” state has been firmly established and agrees nicely with the LQCD prediction; the long-awaited η'_c has also been firmly established with a small hyper-fine mass splitting to the ψ' ; several analyses are confronting the color octet production model; V-P states have finally been observed in ψ' decay with suppressions relative to J/ψ decay of

roughly a factor of 50; while more is being learned about the nature of the $\psi(3770)$, it still remains a puzzle; even more of a mystery is the very narrow state at 3872 MeV! Lots yet to do!

I wish to thank all in the BES, BaBar, Belle, CDF, CLEO and D0 groups who helped me put together this attempt at a selective summary.

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